PRINCIPLES AND CONCEPTS FOR WATER RESOURCES PLANNING UNDER CLIMATE UNCERTAINTY

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ABSTRACT

Possible impacts of a greenhouse warming include changes in precipitation and runoff patterns, sea level rise, land use and population shifts that may follow from these effects, and increased demand for irrigation water in regions with higher temperatures and reduced precipitation. Introducing climate change into the planning process involves a sequence of models and techniques that result in a cascade of uncertainties. Although climate change is not explicitly cited as an issue in the Principles and Guidelines (US Water Resources Council, 1983) used by designated federal water resources agencies, their planning and evaluation principles and methods are flexible enough to incorporate many issues that might arise from the prospect of climate change. Because it can be expensive and time consuming to introduce climate change into planning and project evaluation and the results may be problematical, discretion and guidance are needed. Climate expectations are likely to be particularly important for decisions involving long-lived benefits and costs, irreversibilities, and one-time, unique investments. When it is determined that climate change should be introduced into water planning and project evaluation, the Intergovernmental Panel on Climate Change's IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter *et al.,* 1994) provide a framework and detailed approach for assessing the potential impacts and evaluating adaptation strategies.

INTRODUCTION

The *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies*, commonly known as the Principles and Guidelines or the P&G, establish the standards and procedures that designated federal water resources agencies use for planning and evaluating water projects (US Water Resources Council, 1983). The P&G provides planners with detailed guidance for assessing and dealing with uncertain climate, weather, and hydrologic events in the distant future. Climate change, however, is not mentioned explicitly as a source of uncertainty and has not been routinely incorporated into water planning and project evaluation. Yet, there is now broad agreement that a greenhouse warming would have major impacts on both the supplies and demands for water resources. Possible impacts include changes in precipitation and runoff patterns, sea level rise, land use and population shifts that may follow from these effects, and increased demand for irrigation water in regions with higher temperatures and reduced precipitation.

A recently published study sponsored by the US Army Corps of Engineers' Institute for Water Resources (IWR) and Resources for the Future (RFF) examines: (1) the challenges climate change poses to water planners, (2) when water resources planning principles and evaluation criteria should be altered in response to these challenges, and (3) how these criteria might be altered to incorporate the potential impacts of anthropogenically-induced global climate change. The full study was published as a special issue of *Climatic Change* (vol. 37, September 1997) and in book form as *Climate Change and Water Resources Planning Criteria* (Frederick, Major, and Stakhiv, 1997). This paper summarizes some of the results of the IWR/RFF study.

CHALLENGES POSED BY CLIMATE CHANGE

Introducing climate change into the planning process involves a sequence of models and techniques that result in a cascade of uncertainties. The sequence begins with projections of regional atmospheric or surface variables such as temperature and precipitation at grid nodes derived from a long-term general circulation model (GCM) simulation. The GCMs are better at representing large-scale features of the atmosphere such as the evolution of storm fronts than they are at representing precipitation and runoff that are especially important for water planning. Biases of several degrees C are not uncommon in attempts to reproduce seasonal temperature variations, and there is little agreement among the GCMs as to the future direction of changes in precipitation. In addition to the uncertainties as to the direction and magnitude of the climate induced changes, there is uncertainty as to their timing.

The uncertainties escalate as one goes from the large scale of the GCMs to the river basin scale. Lins *et al.,* (1997) discuss two approaches that might help planners overcome the scale problem. One approach uses intermediate-scale or regional climate models to stratify the mean climatic conditions of a region into a set of distinct weather patterns for which the frequencies and characteristics correlate well with temperature, precipitation, floods, and droughts. Combining this information with knowledge of weather characteristics in and around a river basin provides a basis for predicting regional climate variables. An alternative approach uses GCM output to initialize mesoscale or regional climate models. This nested model approach provides estimates of climate variables that are more consistent with actual regional conditions but requires large amounts of computer time and introduces biases in an unknown way because of the incomplete understanding of atmospheric physics and problems associated with the boundary conditions prescribed by the GCMs. Neither approach addresses the fundamental obstacle stemming from the inability of the GCMs to accurately estimate future climate changes.

The next challenge in the sequence involves the use of hydrologic models calibrated and tested with observed streamflow and meteorological data at the river basin level and then forced with downscaled GCM scenarios to produce streamflow patterns that correspond to GCM climate scenarios. The hydrologic models implicitly assume that parameter estimates based on historical data are applicable to alternative climates. While it appears likely that climate change would alter a region's hydrology, the natural noise in the hydrologic record makes it difficult to establish the presence of trends that might be the result of shifts in the climate or other changes. And when trends in observed hydrologic sequences are determined to be statistically significant, introducing this information in planning and evaluation encounters practical questions as to the causal factors and duration of the trends. To evaluate whether such a trend is a consequence of climate change requires a better understanding of how global warming translates into hydrologic change.

Higher temperatures and carbon dioxide (CO_2) fertilization are two factors that might produce significant changes in hydrology even with no change in precipitation patterns. Seasonal disruptions in water supplies of mountainous areas, where snowmelt is an important source of spring and summer runoff, might result if more precipitation falls as rain than snow and the length of the snow storage season is reduced. And research suggests that atmospheric CO_2 levels may affect water availability through its influence on vegetation. The resulting changes in vegetative cover and evapotranspiration rates can alter rainfall-runoff processes, adding uncertainty to the important link between hydrology and ecosystems.

Ecosystems are likely to be particularly vulnerable to climate changes because the natural response times are slow and adaptation mechanisms are limited. While much is known in general about the potentially large ecological impacts of climate change, our inability to forecast these impacts more precisely contributes to the uncertainties confronting water planners. The vulnerability of these systems is complicated by the reality that population growth and economic development contribute to their degradation in complex ways. The ability to model biophysical, social, and economic baselines decades into the future are limited; linking GCMs to these models to develop an integrated assessment of the impacts of climate change on environmental and ecological resources remains a formidable challenge.

Even if we could quantify the impacts of the climate on ecosystems in biophysical units, there would remain the problem of valuing these changes in socioeconomic terms. Current P&G guidelines encourage the use of valuation approaches such as hedonic pricing, travel costs, and contingent valuation (CV) to estimate the value of nonmarketed goods and services. CV is potentially applicable to climate change analysis because it does not depend on observable behavior; in principle, it can be used to estimate nonuse and future values associated with environmental and ecological conditions. However, even if we knew the nature of the climate change and its impact on terrestrial and aquatic ecosystems, the problems of accounting for future changes in values and preferences make it doubtful that current techniques can provide reasonable estimates of the impacts of climate change on nonmarketed goods and services such as ecosystems (McConnell 1997).

Precipitation, temperature, and atmospheric CO_2 levels affect the demand for as well as the supply of water. Water demands for irrigation, the largest offstream water user, are particularly sensitive to these climate variables. The yields and profitability of irrigation relative to dryland farming tend to rise as conditions become hotter and drier. On the other hand, the resulting increase in the demand for water might be countered in part by increased water use efficiency attributable to higher levels of atmospheric CO_2. Other water uses likely to be influenced directly or indirectly by a greenhouse warming include domestic garden and lawn watering; industrial and thermoelectric power cooling; and instream uses such as hydroelectric power generation, navigation, recreation, and maintenance of ecosystems. Water use forecasts, which have been poor in the absence of climate change, become even more questionable as human activities alter the climate.

THE P&G AND CLIMATE CHANGE

Although climate change is not explicitly cited as an issue in the planning process, one of the conclusions of the IWR/RFF study is that the planning and evaluation principles and methods of the P&G are flexible enough to incorporate many issues that might arise from the prospect of climate change. The initial step in the six-step P&G planning process involves the identification of water and related land resources problems. While climate change has not typically been addressed as the source of these problems, its potentially important impacts on the supply and demand for water may justify introducing climate change into the scoping phase of the planning process.

If climate change is identified as a significant planning issue, the second step in the P&G planning process would include a forecast of the impacts of climate change on the region's land and water resources in the absence of a federal project or policy change but with adaptations that would likely occur as a result of normal human responses to the projected changes. The third step involves the formulation of alternative plans consisting of a system of structural and/or nonstructural measures and strategies that address, among other concerns, the projected consequences of climate change. The alternatives are not limited to those that can be implemented under the existing authority of the federal planning agencies. Nonstructural measures that might be considered "include modifications in public policy, management practice, regulatory policy, and pricing policy" (US Water Resources Council 1983, p. 7).

The fourth step involves evaluating the alternatives expected to exist in the future with and without the plan. The P&G specifies that "plans and their effects should be examined to determine the uncertainty inherent in the data or various assumptions of future ... trends" (US Water Resources Council 1983, p. 5). Methods specified in the P&G for dealing with risk and uncertainty include reducing the irreversible or irretrievable commitment of resources and performing sensitivity analyses of the estimated benefits and costs. The final two steps in the planning process involve comparing the alternatives and selecting a recommended plan.

Having determined that the P&G six-step planning process is sufficiently flexible to incorporate consideration of and responses to many possible climate impacts, the challenge is to determine when the prospect of climate change should be introduced and how.

INTRODUCING CLIMATE CHANGE INTO WATER PLANNING

Although climate change is likely to have significant impacts on both the supply and demand for water, dealing with the challenges described above suggest that introducing it into planning and project evaluation can be expensive, time consuming, and the results problematical. Thus, discretion and guidance are needed as to when climate change should be introduced into the planning process. Factors that might influence the desirability of incorporating climate change into the analysis are the level of planning (i.e., national, regional, local, or project), the reliability of GCMs, the hydrologic conditions (e.g., arid or humid), the time horizon of the plan or life of the project, and the purpose of the project (e.g., hydro, flood protection, or water supply).

An initial question is whether, based on GCM results or other analysis, there is reason to expect that a region's climate is likely to change significantly during the life of an anticipated plan or project. If significant climate change is thought to be likely, the next question is whether there is a basis for forming an expectation about the likelihood and nature of the change and its impacts on water resources. Sea level rise and shifts in snowmelt patterns are two climate-related impacts that may be anticipated with sufficient confidence to warrant special attention in planning and to influence investment decisions. And planners in arid and semiarid areas, where runoff is particularly sensitive to temperature and precipitation changes, should also pay special attention to potential climate impacts.

When there is a basis for forming reasonable expectations about the likelihood of climate changes, the relevance of these changes will depend in part on the nature of the project under consideration. Climate changes that occur several decades in the future will have little relevance for decisions involving small incremental expansions in capacity. The planning and design of the vast majority of relatively small water resources infrastructure investments - whether for water supply, stormwater drainage, irrigation systems, or water quality needs - would be little affected by uncertainty as to climate change. Incremental capacity expansion depends primarily on the discount rate and economies of scale (Rogers 1997).

In contrast to investments involving incremental capacity increases, climate expectations are likely to be very important for decisions involving long-lived benefits and costs, irreversibilities, and one-time, unique investments. Situations for which assumptions about future climate and its impacts on hydrologic patterns may be appropriate to incorporate into water resources planning and management decisions include: (1) comprehensive, large-scale river basin or watershed studies; (2) evaluation of large-scale projects on water systems such as the Ohio River lock and dam navigation systems, the Great Lakes water regulation and hydropower system, and the Missouri River reservoir system; and (3) assessment of large contiguous ecosystems of the scale of the Great Lakes and Florida Everglades.

Hobbs *et al.,* (1997) suggest a five-step approach for introducing expectations about climate change into project evaluation. The initial step involves assessing whether or not the project has characteristics such as irreversibility or long-lived benefits and costs that suggest the decision might be significantly affected by climate change. If these features are not present, climate change can be ignored in the evaluation. But if some or all of these characteristics are present, the second step involves evaluating whether or not the net benefits of the decision would be significantly affected under a climate change scenario. If the climate's impact on the net benefits is significant, step 3 assesses the loss of present worth of net benefits (i.e., the regret) that would result if a decision is made under an erroneous assumption of no climate change. If the regret is significant, step 4 involves constructing a decision tree for evaluating the options under two or more climate scenarios. The expected value of the options is evaluated under a range of subjective probabilities for the scenarios. Finally, step 5 involves assessing the net benefits of waiting to learn more about how the region's climate is changing. Delaying an expensive and irreversible project may be a competitive option, especially in view of the prospect that the delay will result in a better understanding as to how the climate is likely to change and impact the supply and demand for water. Hobbs and his coauthors suggest that with current knowledge about the climate, all five steps in the decision process would be justified in only a small percentage of cases.

In recent decades, increases in the financial and environmental costs of developing new freshwater supplies in the United States through infrastructure investments have curbed the use of structural responses to meeting rising water demands and dealing with hydrologic variability and uncertainty. Although new infrastructure investments may eventually be justified to adapt to hydrologic changes resulting from climate change, in the absence of an improved basis for forming expectations as to the magnitude, timing, and the direction of shifts in a region's climate and hydrology, it is difficult to evaluate and justify additional investments based on the prospect of climate change. On the other hand, when projects are to be undertaken anyway, the robustness of alternative designs can be assessed with the help of what-if climate scenarios.

While the uncertainties associated with the prospect of climate change may not provide sufficient basis for building new projects, they do provide added justification for developing water management and allocation institutions that are more flexible and responsive to changes in the underlying water supply and demand conditions. More efficient management of existing supplies and infrastructure and demand management are critical to containing costs and resolving competing claims on the resource. Efficient, flexible water allocation systems designed for current climatic conditions would be expected to also perform well under different climatic conditions. Thus, institutional flexibility that might complement or substitute for infrastructure investments should be an important consideration in water planning and project evaluation under the prospect of global climate change. Institutional assessments are consistent with the P&G guidelines calling for consideration of nonstructural measures such as modifications in management practices, regulations, and pricing policies for addressing problems and opportunities.

When it is determined that climate change should be introduced into water planning and project evaluation, the Intergovernmental Panel on Climate Change's *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations* (Carter *et al*., 1994) provides a framework and detailed approach for assessing the potential impacts and evaluating adaptation strategies. These guidelines involve seven steps: (1) defining the problem; (2) selecting the method(s) of analysis; (3) evaluating the method(s) through feasibility studies, data acquisition and compilation, and model testing; (4) selecting the baseline and the scenarios to be used to project the future with and without climate change; (5) assessing the climate impacts as the differences over the study period between the projected environmental and socio-economic conditions with and without climate change; (6) assessing adaptations to climate change that are likely to occur in the absence of policy changes; and (7) evaluating adaptation strategies. The IPCC Technical Guidelines provide a strong scientific-technical basis for organizing climate information generated by the GCMs. Adopting these guidelines as the standard for climate change impact analysis would facilitate comparisons across continents, watersheds, and regions, thereby providing a better basis for comparing impacts and developing cost-effective responses. The guidelines, which will require periodic updating to incorporate advances in our understanding of climate change and its impacts on factors such as hydrology and human health, should be used for water planning at the river basin and watershed scales.

In spite of the potential for major impacts and substantial surprises, climate-related uncertainties are not expected to be qualitatively different from those stemming from changes in population, incomes, technology, and social values that have traditionally played a central role in water planning and project evaluation. Indeed, changes in these non-climate factors are likely to have a greater influence on the future availability and use of water than changes in the climate. Moreover, our understanding of how these factors are likely to impact future water conditions is probably better for the climate than for the non-climate changes.

In conclusion, the methods of sensitivity analysis, scenario planning, and decision analysis that are encouraged by the Principles and Guidelines are generally appropriate for planning and project evaluation under the prospect of climate change. However, a few of the assumptions and evaluation criteria employed in water planning might warrant review. The assumption of hydrologic stationarity is particularly suspect. Although the natural noise in the hydrologic record makes it difficult to detect nonstationarity in a strictly statistical sense, the process of stating and justifying underlying climate and hydrologic assumptions would help focus attention on the potential importance of climate change for water resources planning and the need for improved understanding of the linkages between them.

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